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Austrian Mirrors: Development of ultra-low-loss cryogenic crystalline coatings (DARPA)

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This status report is submitted as our deliverable for the second performance period spanning November 30, 2014 through April 29, 2015 (item 0001AB).

Update 1. Demonstration of crystalline coatings with enhanced optical performance

During the second period of our seedling effort, Crystalline Mirror Solutions (CMS) has realized significant improvements in the limiting optical loss of mirrors manufactured with our substrate-transferred crystalline coating process. Through the iterative optimization of our micro-fabrication procedure, we can now reliably produce mirrors with scatter and absorption values below 5 ppm. These results represent a major enhancement in optical quality and enable crystalline coatings with loss levels on par with those found in state-of-the-art ion-beam sputtered (IBS) mirrors. This work represents the culmination of nearly two years of work, with a significant scientific effort undertaken to improve the optical performance of these novel coatings through optimization of both the crystal growth and substrate-transfer processes.

As introduced in our proposal, coating Brownian noise, driven by excess mechanical dissipation in high-reflectivity IBS-derived films, imposes a severe limit on the performance of state-of-the-art precision measurement systems, such as cavity-stabilized lasers for optical atomic clocks and interferometric gravitational wave detectors [1]. As a consequence, a concerted effort has been focused on the identification of optical coatings capable of simultaneously achieving high reflectivity and minimal mechanical dissipation. Building upon advances in semiconductor microfabrication, we have developed a process to integrate low-loss epitaxial multilayers with high-quality mirror substrates. Our innovative coating technology entails the selective removal of crystalline films from the original growth wafer, followed by direct bonding to an arbitrary (curved or planar) optical component. Recently, these "crystalline coatings" have demonstrated an exceptionally low mechanical loss angle of 0(4)×10-5, a tenfold reduction when compared with the best dielectric multilayers at room temperature [2].

Previously, our GaAs/AlGaAs multilayers exhibited typical excess losses (scatter + absorption) at the ~20 ppm level. With a focused effort on minimizing the background impurity level of the constituent films, we can now achieve an optical absorption level below 1 ppm in the near infrared, between 1000-1600 nm. Moreover, by improving the quality of the substrate-transfer process, we have minimized optical scatter losses, reaching limiting levels of ~3 ppm in the same wavelength range. These advancements promise to accelerate the uptake of our coatings into the precision measurement application space, where the simultaneous achievement of high optical and mechanical quality is paramount.

In Figure 1 we present the optical performance of crystalline-coated cavity end mirrors, consisting of 38.5-period (9.50-µm thick) AlGaAs multilayers, with a center wavelength of 1550 nm, directly-bonded to super-polished fused silica substrates (targeting room temperature cavity applications). Position-dependent optical ringdown measurements made by our partners at JILA and Stable Laser Systems in Boulder, CO yield excess loss levels, in the best samples, down to 3 ppm. With a nominal transmission of 10 ppm, these coatings are capable of finesse values exceeding 2×10^5, while a reduction in transmission to 5 ppm would enable a cavity finesse approaching 4×10^5. We expect further reductions in the overall losses at cryogenic temperatures, where carrier freeze out results minimizes impurity driven optical absorption processes [3].

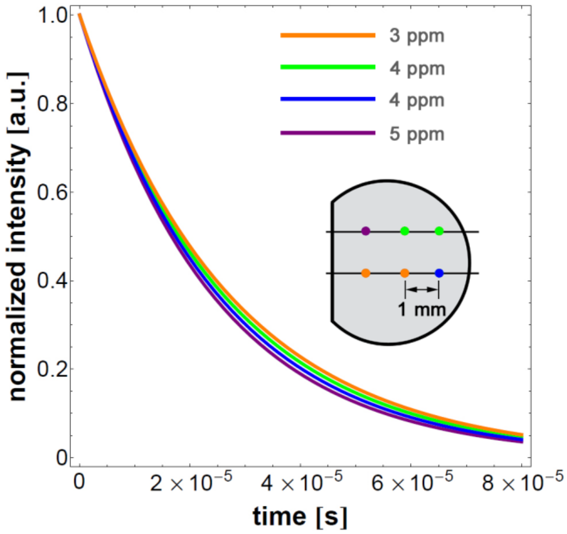

Fig. 1: Position-dependent ringdown of a 1550 nm crystalline coating. Six discrete positions are probed in a 75-mm cavity using a dielectric mirror as the input coupler, yielding excess losses ≤ 5 ppm. Measurements performed by Wei Zhang and Lindsay Sonderhouse of JILA, at Stable Laser Systems in Boulder, CO

Update 2. Development of a high reliability and high-yield AlGaAs-on-Si bonding process

CMS has recently made significant strides in enhancing the yield and reliability achievable in the production of AlGaAs-on-Si cryogenic crystalline coatings. Such coatings will be instrumental for the development of record narrow-linewidth laser systems, building upon the recent demonstration of a cryogenic optical cavity employing single-crystal silicon (SCS) substrates and spacer material [4]. Assuming the post-bond mechanical loss matches that previously observed in microfabricated AlGaAs optomechanical resonators [5], we expect a further tenfold reduction in the mechanical loss angle, to values below 5×10^{-6}. Combining these ultralow-loss crystalline end mirrors with a compact 40-mm long Si spacer, we would then expect to achieve a frequency instability at the 1×10^{-17} level (after 1 s averaging) for operation at 18 K.

As described in our previous report (Deliverable 0001AA), over the course of the last year we have been working in a new cleanroom, namely the UC Santa Barbara nanofabrication facility, and with upgraded bond tooling, the latter being developed together with strategic partners at EV Group, St. Florian am Inn, Austria. With these advancements, we can now reliably produce small-volume production runs of approximately 10 bonded mirror assemblies per week on standard fused silica substrates for room temperature cavity applications. To realize the final deliverables for this effort, targeting the performance levels outlined above, we will ultimately require reliable and high-performance *cryogenic* cavity end mirrors transferred to super-polished SCS substrates.

With our standard fabrication process for AlGaAs-on-silica substrates optimized, we have now turned our attention to the development of a reliable AlGaAs-on-Si transfer process. Along these lines, we have recently made a number of key advancements in this direction, both in terms of the theoretical understanding of the bond strength requirements for such a material combination under these extreme operating conditions, as well as towards the production of prototype cryogenic end mirrors. During this reporting period a test run was undertaken, producing a number of variants of cryogenic crystalline coatings. The completed samples were thermally cycled from room to elevated temperatures (approaching a maximum temperature of 600 K, in steps of 50 K) in order to gauge the maximum thermal strain that the bonded interface could accommodate. The production process that yielded samples surviving to the highest temperatures was then used to prepare two test chips for cryogenic cycling experiments. These tests were carried out in the Quantum Optomechanics Laboratory at the University of Vienna.

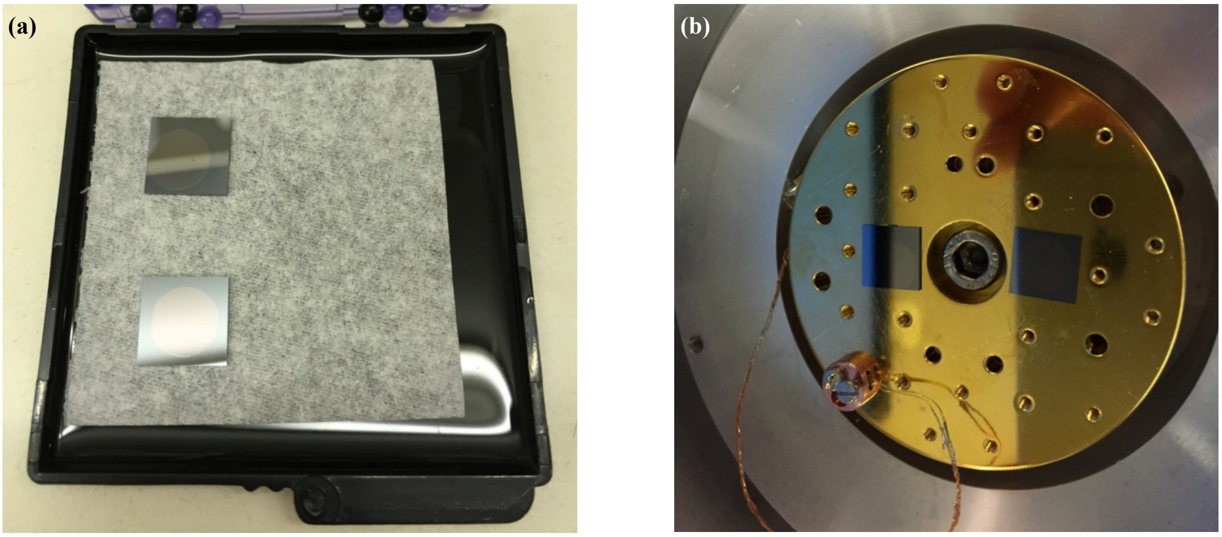

Figure 2. Photographs of optimized AlGaAs-on-Si prototype mirror assemblies. The images show: a) two 1 cm^2 bonded mirrors consisting of 8-mm diameter high-reflectivity GaAs/AlGaAs multilayers on 0.5-mm thick Si chips before loading into the cryostat. Note that each substrate-transferred mirror structure has a small lithographically defined flat to indicate the orientation of the crystalline coating. b) Photographs of the samples after exposure to the cryostat base temperature. In this case the continuous flow ^{4}He system was capable of reaching temperatures <10 K. These samples were subjected to three thermal cycles between 300 K and <10 K and showed no signs of delamination. Thermal cycling experiment performed by Christoph Deutsch, CMS GmbH.

Preliminary work shows that, with this optimized fabrication procedure, the production of high-reliability cryogenic crystalline coatings is indeed feasible. In Figure 2 we include photos of two test structures consisting of high-reflectivity GaAs/AlGaAs multilayers transferred to SCS substrates. We have now realized high-quality and high-reliability crystalline coatings on SCS exhibiting no degradation following three thermal cycles from 300 K to <10 K. It is important to note that this process is a direct extension of that used to produce our standard room temperature optics and utilizes the same basic tooling and unit process steps. Thus, we anticipate (and so far see) no additional manufacturing difficulties, with a typical yield of around 50% for small production volumes (at the 10 unit per week level). We are now waiting on our partners at JILA and SLS to supply us with SCS substrates that we will use to produce the first cryogenic cavity end mirrors with ultralow loss crystalline coatings.

References

1) G. Harry, T. Bodiya, R. DeSalvo, *Optical Coatings and Thermal Noise in Precision Measurement*, Cambridge University Press, 2012.
2) G. D. Cole, W. Zhang, M. J. Martin, J. Ye, M. Aspelmeyer, "Tenfold reduction of Brownian noise in high-reflectivity optical coatings," *Nature Photonics*, vol. 7, no. 8, pp. 644-650, August 2013.
3) Y. A. Akulova, "Vertical-cavity lasers for cryogenic optical interconnects," Ph.D. thesis, University of California, Santa Barbara, USA, 1998.
4) T. Kessler, C. Hagemann, C. Grebing, T. Legero, U. Sterr, F. Riehle, M.J. Martin, L. Chen, J. Ye, "A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity," *Nature Photonics*, vol. 6, no. 9, pp. 687–692, September 2012.
5) G. D. Cole, "Cavity optomechanics with low-noise crystalline mirrors," *SPIE Optics & Photonics, Optical Trapping and Optical Micromanipulation IX*, San Diego, CA, USA, 12–16 August 2012 [8458–07].